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A statistical evaluation of the effects of inverted tooling in a turning operation

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A STATISTICAL EVALUATION
OF THE EFFECTS OF INVERTED TOOLING
IN A TURNING OPERATION

by
Harry Hartman Heist

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25 September 1961
(date)

Sutton Monro
Professor in charge

Arthur F. Gould
Head of the Department

Acknowledgement

For their participation and help in the preparation and completion of this thesis, I offer my many thanks to my friends and Professors at Lehigh University - John Young and Gary Whitehouse with whom I gathered the data and completed the initial analysis, Professor George Kane who first interested me in the field of metal cutting and under whose guidance the data was gathered, Professor Sutton Monro whose patience, help and instruction enabled me to finish this, and finally Linda Heist, my wife, who wouldn't let me rest until this work was finished.

H. H. H.

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CHAPTER I: INTRODUCTION AND PURPOSE

The following thesis is presented to the Graduate Faculty of Lehigh University as the completion of the author's Graduate study in Industrial Engineering. It is the profound desire of the writer that this presentation will accomplish a multiple purpose. First, the author wishes that the reader will fully understand the material as presented; and second, that some reader will use this work as a basis for further study of the problem at hand. It is also this author's desire that the reader will be able to use the methods found here, in other phases of experimental research and analysis.

It is important to become immediately familiar with the stated purposes of this presentation, if you are to understand fully the results of the study. It is equally important that you are aware of the circumstances surrounding the gathering of the data analyzed on the following pages, in order to comprehend exactly what the analyses demonstrate. These data were gathered by three graduate students under the direction of Professor George E. Kane, of the Lehigh University Industrial Engineering Department. A preliminary report, based on a gross analysis of the original data, has been presented to Professor Kane as a requirement of his advanced metal cutting theory course. In short, that report concluded that the results of the original experiment were negative in nature, and that the area of concern demonstrated no real trend or indication of significant relationship to the input variables. With the above as a basis, it will be best to explain next the area studied and the nature of the desired results.

The question, as originally conceived, can be simply stated as follows: "Does the inversion of the cutting tool used in a turning operation have a pronounced effect on the surface roughness of the work?" The basis of this question lies in the consideration of the forces present in a turning operation. Figures 1 and 2, on the next page, show the directional distribution of the forces encountered in a turning operation. When the tool is inverted, the direction of the vertical force on the tool is reversed, with respect to a tool in the normal position.

This force, noted F_t, is acting on the face of the tool, and is normally the largest of the three forces encountered in turning. In the normal position, the vertical force is directed toward the floor or into the supporting members of the machine. Since there is an equal and opposite force on the work piece, there is a tendency for the work to be thrown up and out of the holding fixtures. Conversely, in the inverted position, the vertical force on the tool is directed away from the floor. This means that the work piece is being forced down and out of holding fixtures. In other words, in the regular position the tool post experiences compression, while in the inverted position the tool post is in tension. Since the direction of feed is the same in both applications, the longitudinal, or feed force, does not change direction. There is no reason to believe that the magnitudes of these forces would be affected by the tool position, so it will be assumed that the forces change only in direction.

At this point, the original question can be amended to read: "Does the reversal in direction of the vertical force encountered in a turning

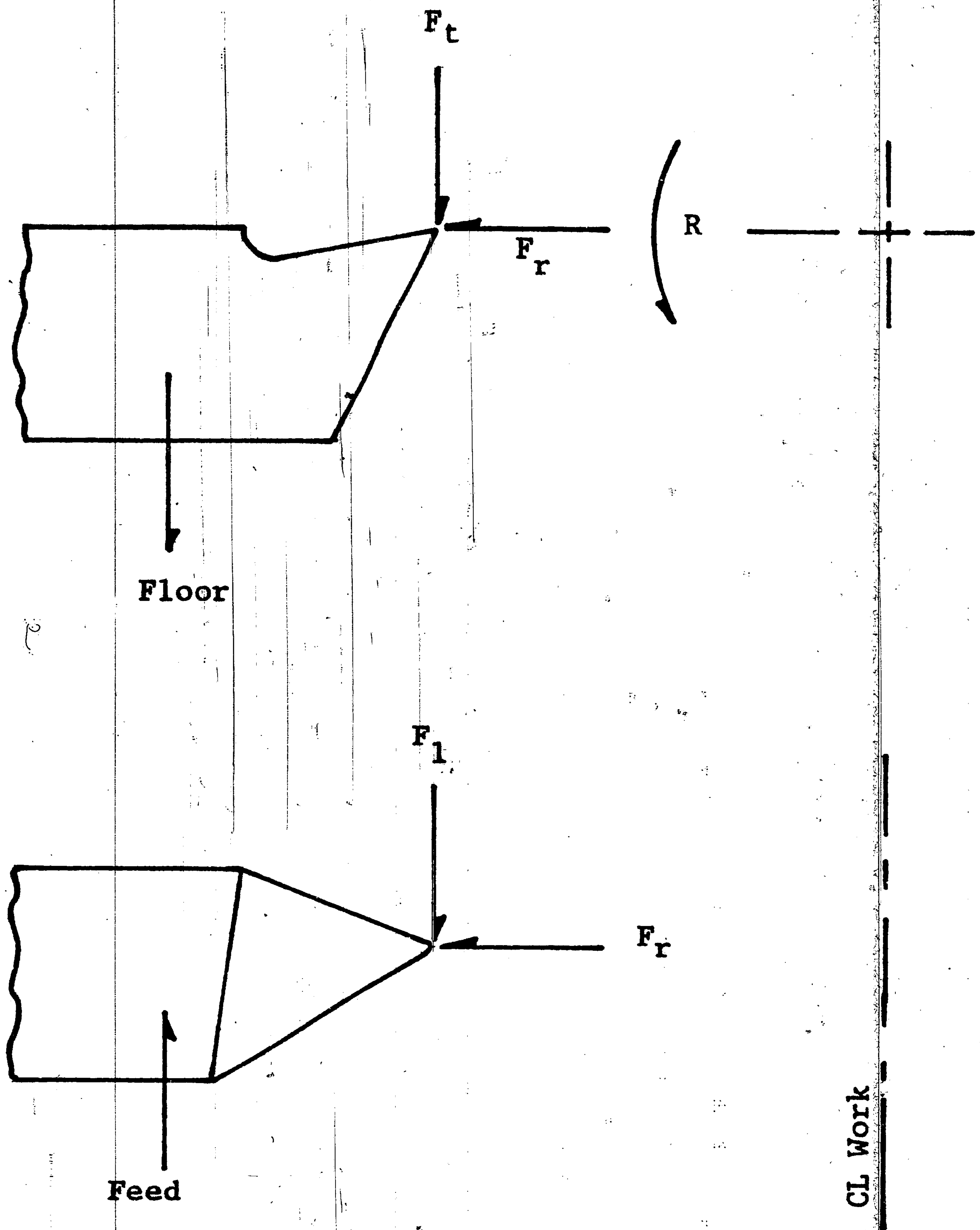


Fig. No. 1

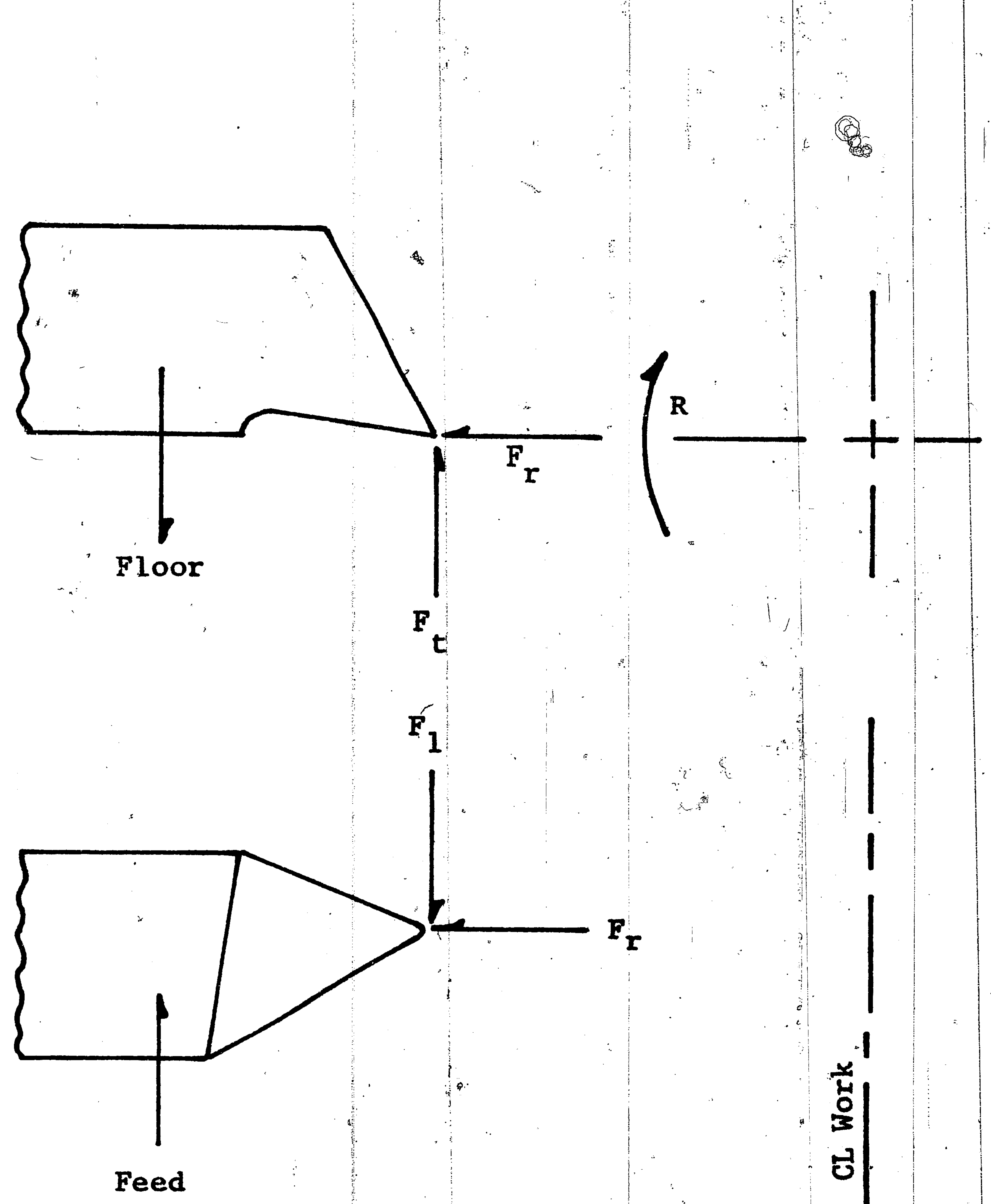


Fig. No. 2

operation have a significant effect on the surface roughness of the work?" It is assumed, in the above question, that all other factors remain constant. The answer to this question is the primary function of this thesis.

It should be noted that since there was no equipment available to measure the actual magnitude of the forces encountered, the assumption regarding force magnitude had to be made. This would seem to be a logical assumption, and there is no available literature which would suggest the contrary. The writer does not mean to imply that forces are the singular causes of a resultant surface finish. What is implied, however, is that if all the other factors which do contribute to surface finish are held constant, the direction of the forces, as applied to both the work and tool, may have a significant effect on the surface finish generated by the operation.

It would seem obvious, therefore, that the primary intent of this thesis is to expand the original analysis of the data. This is true to a great extent, but must be slightly modified by two underlying conditions. First, the original analysis was rough in nature and made no attempt to draw all of the available information out of the data. It is this writer's opinion that the additional information contained in the data will add substantially to the complete understanding of the answer to the question stated previously. Such information can only be extracted by means of a more careful and thorough analysis than was originally undertaken. Secondly, the writer feels that there is room for much additional research on this question. Therefore, this thesis is also presented as an aid to those who wish to continue in this field. It is hoped that the knowledge gained through the study of this paper will enable others to proceed without much duplication of effort, and in a manner that will circumvent the problems found in this experiment.

CHAPTER 2: EXPERIMENTAL DESIGN AND PROCEDURE

The experiment discussed in this paper was conducted in the Manufacturing Processes Laboratory of Lehigh University's Industrial Engineering Department. All of the equipment used was that which is normally a part of the laboratory, and no modifications were made especially for this research. The equipment set-up was different than that normally used, but required no actual alteration of the lathe. Table 1, on the next page, lists all of the equipment and materials used. The tools and tool holders were selected at random from the laboratory's supply, and no measurements were taken to verify the manufacturer's specifications. The material used was four consecutive lengths, cut from the same bar, and therefore came from the same heat. Originally, the stock was six inches in diameter, and had been reduced to the size used here in previous experiments. Brinnell Hardness readings were taken on the surface and along the diameter of each length. In each case, the reading was 300 $\pm$ 5. A reading was also taken at the conclusion of the experiment to test for work hardening. This test showed no appreciable change in the hardness.

The actual machine set-up was straightforward and simple. Figure 3 shows exactly how the tools were positioned for the experiment. This set-up insured the duplication of conditions for each tool position. The tool holders were fitted on the tool posts so that the tips of the tools were within $\pm$ 0.002 inches of the axis of rotation in the horizontal plane. They were also positioned so that the tool tips were within 0.03125 inches of each other in the vertical plane. The material was extended 12.00 $\pm$ 0.0625 inches from the chuck, and ran free on one end. As indicated in Figure 4, three of the five feeds were run on one end of the bar, and the

TABLE NO. 1: EXPERIMENTAL EQUIPMENT AND MATERIALS

1. One (1) Warner & Swasey No. 5 Turret Lathe

2. One (1) Profilometer, Root Mean Square summation over 0.030 of an inch, hand trace used.

3. Two (2) SQ-162U4 Tungsten-Carbide Disposable Inserts - Carbaloy - Grade 370; eight (8) edges each.

Side	0.500 ± 0.005" Square
Thickness	0.125 ± 0.005"
Nose Radius	0.0625"

4. Two (2) Carbaloy SB-R-16 Tool Holders - Right Hand

Side Rake	-5°
Back Rake	-5°
Front Relief	5°
Side Relief	5°
Side Cutting Edge Angle	15°
End Cutting Edge Angle	15°
Shank	1" x 1" x 6"

5. Four (4) Bars 4145 H. R. S.

B. H. No. 300	
Initial Diameter	2.750" (approx.)
Length	30" (approx.)

6. One (1) 2 - 3" Micrometer .00X"

7. Depth of Cut - 0.020"

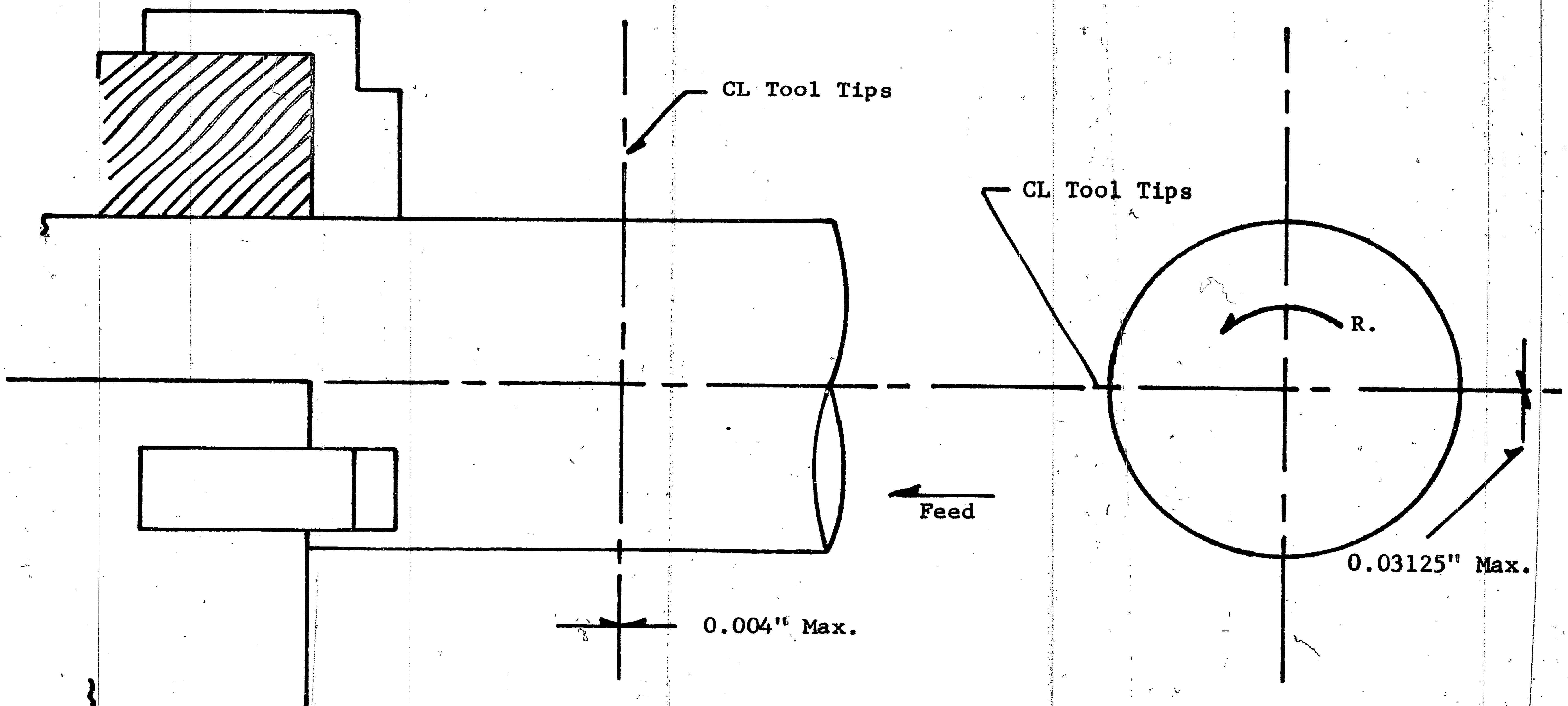


Fig. 3 - Turret Lathe Set Up

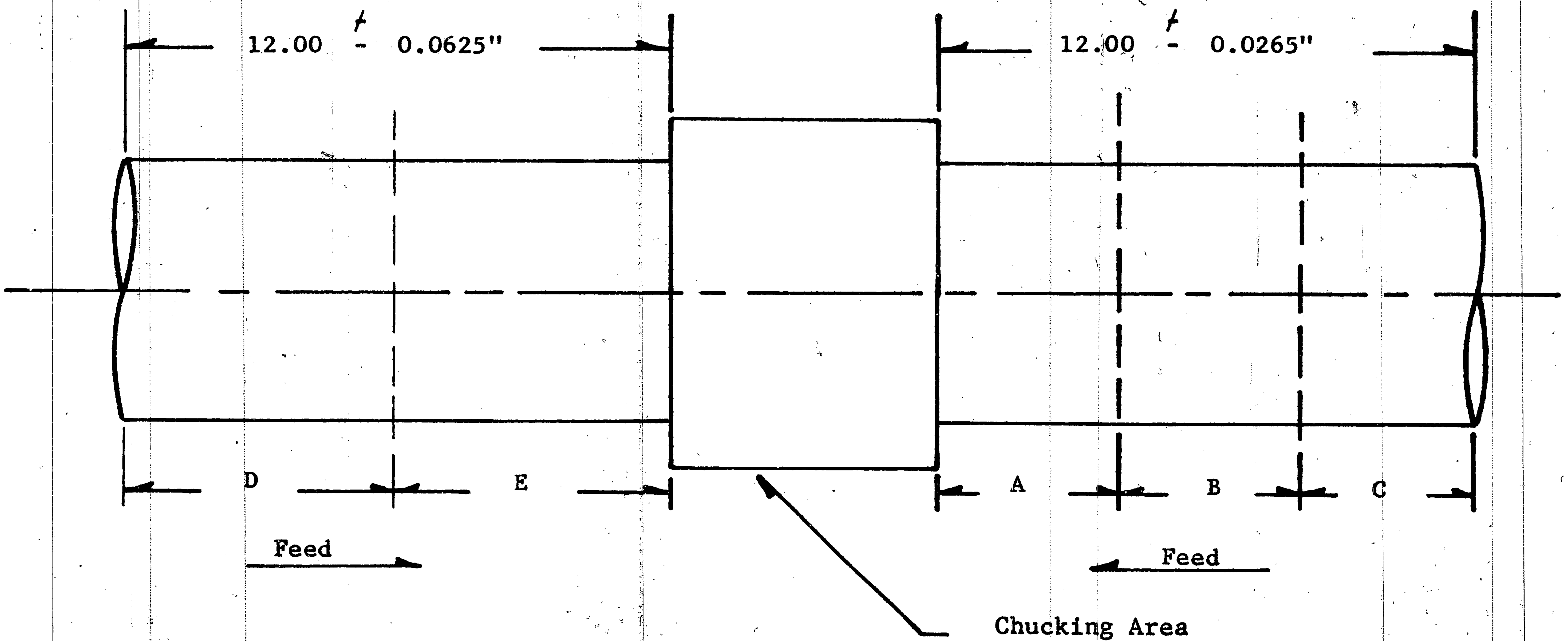


Fig. 4 - Work Piece Set Up

remaining two on the other end. A total of four bars was used and each was used twice. The procedure was first to run the three low feeds, over the five speeds, at one end of the bar, using one tool position. After reversing and truing the bar, the two high feeds were run on the second end. When each of the feeds was run over each of the speeds, for one tool position, the bar was removed from the lathe. A new bar was positioned in the chuck and the above procedure repeated, using the second tool position. After each complete run of five feeds and four speeds, the tool was rotated to expose a new edge. In this manner, two replications of each feed and speed combination, and for both tool positions, were obtained. These eighty readings will be referred to as Set I in future discussions. At this point, the group felt that it would be advantageous to obtain more data. In order to do this, the procedure outlined above was repeated, and eighty additional readings were obtained. These readings will be referred to as Set II. Note that since only four bars were used, the initial diameters of the bars in Set II were smaller than those in Set I. This means that although only four R.P.M. values were used, the data shows eight values of surface feet per minute. The inability to completely replicate the first set, caused many difficulties in the analysis of the data.

It is also important that the exact procedures followed in the actual gathering of the data be explained. In any experiment, it is highly possible that the person or persons doing the research will introduce a bias into the results. In order to reduce this effect, the experiment was conducted in a manner that would serve to minimize personal bias. This end was partially accomplished by assigning a specific job to each member of the group. John Young ran the lathe, making the depth settings, adjusting the feeds, placing the stock in the exact position, and measuring the bar diameters. Gary Whitehouse operated the profilameter and traced the generated surfaces. The writer acted as data taker, read the profilometer, and made the speed adjustments. It was particularly important that the same person do all of the tracing, and that another person always read the profilometer scale. The reason for the above statement is that the profilometer is particularly susceptible to operator bias.(1) Each member of the group carried out his, and only his, assignment, and thus the original plan was preserved.

One final point should be made before examining the actual data. Due to the fact that certain readings were lost or discarded during the course of the experiment, there are eight missing values in the final data sheet. These values, along with the others which deserved special consideration, are noted in the following tables. The tables found on the next eight pages include all of the values taken during the course of the experiment, and all other useful information. By way of explanation, the column headed "AREA" indicates the section of the test specimens, as shown in Figure 4, from which the reading was taken.

There is much to be gained from a careful study of these data. A thorough investigation of the data indicates that two groups of problems

(1) Heist, H. H., and Whitehouse, G.E., "Analysis of Instrumentation in Manufacturing Processes Laboratory at Lehigh University." A report prepared for Prof. G. E. Kane of Lehigh University, 1961.

Heist, H. H., and Whitehouse, G.E., "Summary Report for Industrial Engineering 140 on the Capabilities of the Manufacturing Processes Laboratory's Instrumentation, 1961." On file in Manufacturing Processes Laboratory of Lehigh University.

TABLE NO. 2: EXPERIMENTAL DATA - FRONT POSITION - SET I

Date of Run	R.P.M.	Feed In./Rev.	Micro-In.	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA	Bar
11/29/60	324	0.045	(1) 200	2.623	2.585	220	A	1
12/ 6/60	"	"	100	2.623	2.585	"	A	2
11/29/60	"	0.007	110	2.623	2.586	"	B	1
12/ 6/60	"	"	90	2.623	2.586	"	B	2
11/29/60	"	0.012	150	2.623	2.587	"	C	1
12/ 6/60	"	"	(2) 550	2.623	2.587	"	C	2
11/29/60	444	0.0045	(3) 230	2.585	2.546	296	A	1
12/ 6/60	"	"	81	2.585	2.547	"	A	2
11/29/60	"	0.007	90	2.586	2.547	"	B	1
12/ 6/60	"	"	74	2.586	2.547	"	B	2
11/29/60	"	0.012	140	2.587	2.548	"	C	1
12/ 6/60	"	"	76	2.587	2.548	"	C	2
11/29/60	606	0.0045	70	2.546	2.506	398	A	1
12/ 6/60	"	"	58	2.547	2.507	"	A	2
11/29/60	"	0.007	85	2.547	2.507	"	B	1
12/ 6/60	"	"	76	2.547	2.507	"	B	2
11/29/60	"	0.012	130	2.548	2.508	"	C	1
12/ 6/60	"	"	110	2.548	2.508	"	C	2
11/29/60	830	0.0045	65	2.506	2.466	536	A	1
12/ 6/60	"	"	56	2.507	2.467	"	A	2
11/29/60	"	0.007	70	2.507	2.467	"	B	1
12/ 6/60	"	"	(4) 140	2.507	2.467	"	B	2
11/29/60	"	0.012	120	2.508	2.468	"	C	1
12/ 6/60	"	"	110	2.508	2.468	"	C	2

TABLE NO. 2: EXPERIMENTAL DATA - FRONT POSITION - SET I (cont'd)

Date of Run	R.P.M.	Feed In./Rev.	Micro-In.	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA	Bar
11/29/60	324	0.019	290	2.626	2.590	220	D	1
12/ 6/60	"	"	280	2.625	2.598	220	D	2
11/29/60	"	0.029	625	2.626	2.591	220	E	1
12/ 6/60	"	"	490	2.625	2.600	220	E	2
11/29/60	444	0.019	325	2.590	2.550	296	D	1
12/ 6/60	"	"	240	2.588	2.558	"	D	2
11/29/60	"	0.029	600	2.591	2.551	"	E	1
12/ 6/60	"	"	475	2.600	2.560	"	E	2
11/29/60	606	0.019	325	2.550	2.510	398	D	1
12/ 6/60	"	"	250	2.558	2.512	"	D	2
11/29/60	"	0.029	625	2.551	2.511	"	E	1
12/ 6/60	"	"	480	2.560	2.513	"	E	2
11/29/60	830	0.019	300	2.510	2.470	536	D	1
12/ 6/60	"	"	250	2.512	2.472	"	D	2
11/29/60	"	0.029	650	2.511	2.470	"	E	1
12/ 6/60	"	"	500	2.513	2.474	"	E	2

(1) Light chatter, discarded
(2) Heavy chatter, discarded
(3) Light chatter, discarded
(4) Varied roughness over cut, discarded

TABLE NO. 3: EXPERIMENTAL DATA - INVERTED POSITION - SET I

Date of Run	R.P.M.	Feed In./Rev.	Micro-In.	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA	Bar
12/ 1/60	324	0.0045	110	2.621	2.587	220	A	3
12/ 8/60	"	"	50	2.626	2.583	"	A	4
12/ 1/60	"	0.007	100	2.621	2.589	"	B	3
12/ 8/60	"	"	70	2.626	2.583	"	B	4
12/ 1/60	"	0.012	150	2.621	2.591	"	C	3
12/ 8/60	"	"	160	2.626	2.587	"	C	4
12/ 1/60	444	0.0045	65	2.587	2.547	296	A	3
12/ 8/60	"	"	50	2.583	2.538	"	A	4
12/ 1/60	"	0.007	80	2.589	2.549	"	B	3
12/ 8/60	"	"	65	2.583	2.542	"	B	4
12/ 1/60	"	0.012	100	2.591	2.553	"	C	3
12/ 8/60	"	"	130	2.587	2.538	"	C	4
12/ 1/60	606	0.0045	40	2.547	2.507	398	A	3
12/ 8/60	"	"	(5) 85	2.538	2.498	"	A	4
12/ 1/60	"	0.007	70	2.549	2.509	"	B	3
12/ 8/60	"	"	75	2.542	2.500	"	B	4
12/ 1/60	"	0.012	100	2.553	2.512	"	C	3
12/ 8/60	"	"	120	2.538	2.505	"	C	4
12/ 1/60	830	0.0045	55	2.507	2.467	536	A	3
12/ 8/60	"	"	(6) 85	2.498	2.458	"	A	4
12/ 1/60	"	0.007	70	2.509	2.470	"	B	3
12/ 8/60	"	"	70	2.500	2.467	"	B	4
12/ 1/60	"	0.012	110	2.512	2.472	"	C	3
12/ 8/60	"	"	120	2.505	2.465	"	C	4

TABLE NO. 3: EXPERIMENTAL DATA - INVERTED POSITION - SET I (cont'd)

Date of Run	R.P.M.	Feed In./Rev.	Micro-In. (7)	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA	Bar
12/ 1/60	324	0.019	200	2.623	2.595	220	D	3
12/ 8/60	"	"	230	2.628	2.593	"	D	4
12/ 1/60	"	0.029	600	2.623	2.595	"	E	3
12/ 8/60	"	"	450	2.628	2.593	"	E	4
12/ 1/60	444	0.019	175	2.595	2.552	296	D	3
12/ 8/60	"	"	230	2.593	2.552	"	D	4
12/ 1/60	"	0.029	550	2.595	2.552	"	E	3
12/ 8/60	"	"	470	2.593	2.550	"	E	4
12/ 1/60	606	0.019	185	2.552	2.512	398	D	3
12/ 8/60	"	"	210	2.552	2.512	"	D	4
12/ 1/60	"	0.029	510	2.552	2.512	"	E	3
12/ 8/60	"	"	390	2.550	2.510	"	E	4
12/ 1/60	830	0.019	175	2.512	2.473	536	D	3
12/ 8/60	"	"	220	2.512	2.472	"	D	4
12/ 1/60	"	0.029	500	2.512	2.472	"	E	3
12/ 8/60	"	"	430	2.510	2.471	"	E	4

(5) Chips rubbed surface, discarded
(6) Chips rubbed surface, discarded
(7) Chatter - 4 inches

TABLE NO. 4: EXPERIMENTAL DATA - FRONT POSITION - SET II

Date of Run	R.P.M.	Feed In./Rev.	Micro-In.	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA	Bar*
12/14/60	324	0.0045	170	2.431	2.394	204	A	
12/15/60	"	"	140	2.429	2.389	"	A	
12/14/60	"	0.007	200	2.431	2.393	"	B	
12/15/60	"	"	(8) 250	2.429	2.390	"	B	
12/14/60	"	0.012	130	2.431	2.395	"	C	
12/15/60	"	"	125	2.429	2.391	"	C	
12/14/60	444	0.0045	65	2.394	2.355	275	A	
12/15/60	"	"	110	2.389	2.350	"	A	
12/14/60	"	0.007	75	2.393	2.355	"	B	
12/15/60	"	"	110	2.390	2.349	"	B	
12/14/60	"	0.012	130	2.395	2.357	"	C	
12/15/60	"	"	125	2.391	2.351	"	C	
12/14/60	606	0.0045	58	2.355	2.315	368	A	
12/15/60	"	"	85	2.350	2.310	"	A	
12/14/60	"	0.007	85	2.355	2.315	"	B	
12/15/60	"	"	80	2.349	2.310	"	B	
12/14/60	"	0.012	100	2.357	2.316	"	C	
12/15/60	"	"	100	2.351	2.311	"	C	
12/14/60	830	0.0045	50	2.315	2.276	495	A	
12/15/60	"	"	100	2.310	2.269	"	A	
12/14/60	"	0.007	80	2.315	2.276	"	B	
12/15/60	"	"	120	2.310	2.270	"	B	
12/14/60	"	0.012	110	2.316	(9) 2.235	"	C	
12/15/60	"	"	100	2.311	2.270	"	C	

* Bar numbers unknown for Set II

TABLE NO.4: EXPERIMENTAL DATA - FRONT POSITION - SET II

Date of Run	R.P.M.	Feed In./Rev.	Micro-In.	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA
12/14/60	324	0.019	180	2.432	2.397	204	D
12/15/60	"	"	230	2.436	2.400	"	D
12/14/60	"	0.029	(10) -	2.432	(11) -	"	E
12/15/60	"	"	450	2.436	2.402	"	E
12/14/60	444	0.019	210	2.397	2.359	275	D
12/15/60	"	"	220	2.400	2.359	"	D
12/14/60	"	0.029	425	-	2.361	"	E
12/15/60	"	"	550	2.402	2.360	"	E
12/14/60	606	0.019	220	2.359	2.320	368	D
12/15/60	"	"	220	2.359	2.319	"	D
12/14/60	"	0.029	450	2.361	2.319	"	E
12/15/60	"	"	425	2.360	2.320	"	E
12/14/60	830	0.019	210	2.320	2.280	495	D
12/15/60	"	"	240	2.319	2.278	"	D
12/14/60	"	0.029	450	2.319	2.281	"	E
12/15/60	"	"	525	2.320	2.281	"	E

(8) Light chatter
(9) Depth of cut increased to 0.040"
(10) No reading, feed not changed
(11) No reading taken

TABLE NO. 5: EXPERIMENTAL DATA - INVERTED POSITION - SET II

Date of Run	R.P.M.	Feed In./Rev.	Micro-In.	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA
12/15/60	324	0.0045	140	2.430	2.389	204	A
12/15/60	"	0.0045	140	2.432	2.389	"	A
12/15/60	"	0.007	130	2.430	2.392	"	B
12/15/60	"	"	145	2.432	2.391	"	B
12/15/60	"	0.012	(12) ---	2.430	2.396	"	C
12/15/60	"	0.012	150	2.432	2.395	"	C
12/15/60	444	0.0045	95	2.389	2.350	275	A
12/15/60	"	"	100	2.389	2.350	"	A
12/15/60	"	0.007	85	2.392	2.352	"	B
12/15/60	"	"	120	2.391	2.353	"	B
12/15/60	"	0.012	110	2.396	2.355	"	C
12/15/60	"	"	160	2.395	2.356	"	C
12/15/60	606	0.0045	70	2.350	2.310	368	A
12/15/60	"	"	110	2.350	2.310	"	A
12/15/60	"	0.007	75	2.352	2.312	"	B
12/15/60	"	"	120	2.353	2.313	"	B
12/15/60	"	0.012	100	2.355	2.316	"	C
12/15/60	"	"	165	2.356	2.316	"	C
12/15/60	830	0.0045	65	2.310	2.270	495	A
12/15/60	"	"	70	2.310	2.276	"	A
12/15/60	"	0.007	70	2.312	2.272	"	B
12/15/60	"	"	110	2.313	2.273	"	B
12/15/60	"	0.012	110	2.316	2.276	"	C
12/15/60	"	"	150	2.316	2.276	"	C

TABLE NO. 5: EXPERIMENTAL DATA - INVERTED POSITION - SET II (cont'd)

Date of Run	R.P.M.	Feed In./Rev.	Micro-In.	Initial Diam.-In.	Final Diam.-In.	S.F.P.M.	AREA
12/15/60	324	0.019	350	2.430	2.394	204	D
12/15/60	"	"	260	2.431	2.396	"	D
12/15/60	"	0.029	550	2.430	2.394	"	E
12/15/60	"	"	500	2.431	2.397	"	E
12/15/60	444	0.019	315	2.394	2.355	275	D
12/15/60	"	"	290	2.396	2.359	"	D
12/15/60	"	0.029	565	2.394	2.354	"	E
12/15/60	"	"	500	2.397	2.356	"	E
12/15/60	606	0.019	310	2.353	2.314	368	D
12/15/60	"	"	300	2.359	2.319	"	D
12/15/60	"	0.029	610	2.354	2.316	"	E
12/15/60	"	"	550	2.356	2.316	"	E
12/15/60	830	0.019	300	2.314	2.275	495	D
12/15/60	"	"	280	2.319	2.278	"	D
12/15/60	"	0.029	600	2.316	2.274	"	E
12/15/60	"	"	525	2.316	2.276	"	E

(12) Chatter, too heavy to measure surface finish

arise. First, there are those considerations concerning metal cutting theory. The particular combinations of feeds and speeds used in the experiment violate two basic metal cutting theories. In one case, the two lowest values of speed, 204 and 220 S.F.P.M., are very near the lower speed limit for carbide tools. This means that the tools are inefficient, in their cutting action, at these speeds. The above fact will have a decided effect on the surface finish obtained. In the second case, the highest two feeds, 0.019 and 0.029 inches per revolution, are normally used for roughing cuts. In effect, this means the operator is not usually concerned about the finishes generated at these feeds. Once again, the inclusion of the data obtained under these conditions will have a pronounced effect upon the results gained through a statistical analysis.

A second group of problems are centered around the design and statistical consistency of the experiment. As was mentioned previously, the revised data include eight missing values. What should be done about these missing observations? Further examination of the data reveals the fact that neither the values of surface feet per minute nor feed increase in any consistent pattern. In other words, there is a lack of equal steps in either direction. Finally, there is the problem of how the eight different values of speed should be treated. Each of these questions must be investigated and resolved before a meaningful analysis of the data can be undertaken. Chapter Three is devoted to the problems of analysis, and will demonstrate how the writer answered each of the above-mentioned questions.

CHAPTER 3 THE ANALYSIS

Before undertaking the formal analysis, certain doubts about the appearance of the data must be fully resolved if maximum understanding is to be achieved. In Chapter 2, it was noted that there were certain obvious problem areas. The first of these concerned which segments of the data should be kept or discarded for the purpose of analysis. This consideration takes two distinct forms. On one hand, there is the applicability to metal cutting theory. It was previously mentioned that two of the feeds and two of the speeds included in the experiment are outside of the normal range of consideration with regard to surface finish. These high feeds and low speeds are known to produce finishes not generally held to exacting requirements, and therefore logically should be discarded. The main drawback here is the consideration of whether or not the discarding of these data would be beneficial to the experiment as a whole. One must remember that these readings were taken under the same conditions as the rest, and therefore should be as representative of the actual results as the other readings.

What would be the effect of including or deleting these readings? The major analysis of the data consists of comparing one reading with its counterpart, and these questionable data should not introduce any especially significant errors. One real effect of including these data will be apparent, however, and will serve as a block to one type of analysis. It is obvious that as variables and replications are added to an experiment, the function explaining the relationships present will increase in complexity. It is commonly understood that two points describe a straight line, and three points describe a simple curve. As more points are added, however, the curve usually becomes more complex. The same is true in this experiment. The addition of any variables or readings serves to further complicate the relationship between these variables and surface finish. For the purposes of this study, the writer feels that the increased complexity of the mathematical function describing the relationships of the input variables to surface finish is not particularly harmful. With this understanding, these data will be included in the analysis, but the results drawn from the experiment will be modified by the consideration of the effects of including these data.

The second part of the data which must be considered, is that group of readings which were taken under questionable conditions. These readings are noted in Tables 2 - 5, and should be referred to at this time. It would seem logical to discard only those readings which displayed a marked deviation from their exact counterpart. By following this procedure, the analyst assumes that replication of an experiment produces similar results. He also assumes that when one reading of an exact pair or group is markedly different from the other(s), the difference is caused by uncontrolled conditions. It should be obvious, however, that the discarding of data is correct only when the analyst has a substantial reason to believe that the data is not truly representative of the process. It would not be proper to discard a reading simply because it looked different from the rest. In this experiment, however, there was proof, through observation, that these data were not truly representative of the process, and therefore they were discarded.

The question now arises as to how these readings are to be replaced. It is worthy to note that, for the method of analysis used in this study, the data had to be complete. This is due to a requirement of the computer program used for the mathematical analysis. There is, however, a choice as to the exact method of value replacement. In his book, "Industrial Experimentation",[2] K.A. Brownlee proposes a method for the replacement of missing values. This method is based on the minimization of the error sum of squares. Brownlee presents two examples of this method, one for each two-factor and multi-factor experiment. This writer decided to compare Brownlee's method with one based on intuitive reasoning. The mathematical comparison of these two methods is illustrated on the first two pages of the appendix to this paper. As can be seen by referring to these calculations, the differences between the proposed and intuitive methods is relatively small. Differences of this small magnitude should not have a significant effect on the results of the analysis, and the additional accuracy obtained through such calculations is not proportional to the effort expended in deriving the new values. By way of explanation, the method of replacement used in this analysis consisted of substituting the reading from the remaining replication for the discarded value. The readings replaced were those noted in Tables 2 - 5. The procedure followed does tend to reduce the sum of squares about the mean, as it does remove some source of variation.

There is, however, one major effect of this, or any other, method of replacement. The effect shows up in the number of degrees of freedom associated with the residual or four factor interaction term. Since the original data has been altered, and one source of variation removed, one degree of freedom must be subtracted from the total for each replacement. This procedure was followed throughout the following analyses.

In Chapter 2, one other problem area was mentioned. This question

(2) Brownlee, K.A., Industrial Experimentation, New York, N.Y.: Chemical Publishing Co., Inc., 1953

dealt with the lack of equal steps between the values of the two input variables, feed and speed. Although this situation does not have a pronounced effect on the analysis of the data, it does tend to dictate the type of analysis used. One type of examination commonly used in research is regression analysis. This may have been a useful tool in this experiment too. The lack of equal spaces between the values of the input variables makes this type of analysis much more difficult, and does prevent simple regression analysis.

As was mentioned previously, the actual mathematical analysis of the data was done by a computer. The particular technique used was the Fisher Variance Ratio Test. This test, and the information required to perform it, gives the analyst an excellent insight into the true effects of both the input variables and their interactions. The remainder of this chapter is devoted to a discussion of the results obtained through the analysis. A sample of the computer output is shown on the third page of the appendix. This sample shows the unmodified analysis of the data. Tables 6, 7, and 8, on the following pages, list the amended data, the analysis as modified with respect to degrees of freedom, and the mathematical results of the ratio tests.

As an aid to the reader, the following terms will be used in the discussion of the individual analyses.

1) Set I: Those readings taken on the bar (s) at the maximum diameters. This set is identified by the speed notations 220, 296, 398, and 536 S.F.P.M.

2) Set II: Those readings taken on the bar (s) at the minimum diameters. This set is identified by the speed notations 204, 275, 368, and 495 S.F.P.M.

TABLE NO. 6: REVISED DATA

S.F.P.M.	Feed - Inches Per Revolution										
	0.0045		0.007		0.012		0.019		0.029		Test
	Reg.	Inv.	R	I	R	I	R	I	R	I	
Set #I											
220	100	110	110	100	150	150	290	200	625	600	1
220	100	50	90	70	150	160	280	230	490	450	2
296	81	65	90	80	140	100	325	175	600	550	1
296	81	50	74	65	76	130	240	230	475	470	2
398	70	40	85	70	130	100	325	185	625	510	1
398	58	40	76	75	110	120	250	210	480	390	2
536	65	55	70	70	120	110	300	175	650	500	1
536	56	55	70	70	110	120	250	220	500	430	2
Set #II											
204	170	140	200	130	130	150	180	350	450	550	3
204	140	140	250	145	125	150	230	260	450	500	4
275	65	95	75	85	80	110	210	315	425	565	3
275	110	100	110	120	125	160	220	290	550	550	4
368	58	70	85	75	100	110	220	310	450	610	3
368	75	110	80	120	100	165	220	300	425	550	4
495	50	65	80	70	110	110	210	300	450	600	3
495	100	70	120	110	100	150	240	280	525	525	4

TABLE NO. 7 - COMBINED ANALYSIS

Source	D.F.	Mean Square	F.Ratio
Speed	7	4,270	4.6
Feed	4	1,054,903	1,146
Tool	1	82	-
Replication	1	3,543	3.8
S-F	28	1,640	1.7
S-T	7	8,319	9.0
S-R	7	3,290	3.5
F-T	4	1,119	1.2
F-R	4	7,477	8.1
T-R	1	96	-
S-F-T	28	2,391	2.5
S-F-R	28	833	-
S-T-R	7	1,960	2.1
F-T-R	4	1,292	1.4
S-F-T-R	20	920	
Total	151		

	Set I			Set II		
Source	D.F.	Mean Square	F.Ratio	D.F.	Mean Square	F.Ratio
Speed	3	3,204	10.6	3	4,046	11.6
Feed	4	572,409	1,901	4	485,709	972
Tool	1	24,047	79.8	1	28,200	60.0
Replication	1	19,375	64.3	1	3,025	6.4
S-F	12	248	-	12	2,507	5.3
S-T	3	492	1.6	3	1,532	3.2
S-R	3	154	-	3	1,238	2.6
F-T	4	5,329	17.7	4	9,409	20.0
F-R	4	10,341	34.3	4	1,123	2.4
T-R	1	4,883	16.2	1	3,150	6.7
S-F-T	12	424	1.4	12	615	1.3
S-F-R	12	201	-	12	414	-
S-T-R	3	865	2.8	3	1,064	2.3
F-T-R	4	1,727	5.7	4	2,536	5.4
S-F-T-R	6	301		10	471	
Total	73			77		

TABLE NO. 8 - ANALYSIS OF VARIANCE - SUMMARY

	Combined Analysis				Set I				Set II			
SOURCE	DF.	F.	Lev.	Val.*	DF	F.	Lev.	Val.	DF.	F.	Lev.	Val.
Speed	7	4.6	0.01	3.9	3	10.6	0.01	9.8	3	11.6	0.01	6.6
Feed	4	1,146	0.001	7.1	4	1,901	0.001	21.9	4	972	0.001	11.3
Tool	1	-	-	-	1	79.8	0.001	35.5	1	60	0.001	21.0
Replication	1	3.8	-	-	1	64.3	0.001	35.5	1	6.4	0.05	5.0
S-F	28	1.7	-	-	12	-	-	-	12	5.3	0.01	4.7
S-T	7	9.0	0.001	6.0	3	1.6	-	-	3	3.2	-	-
S-R	7	3.5	0.05	2.6	3	-	-	-	3	2.6	-	-
F-T	4	1.2	-	-	4	17.7	0.01	9.2	4	20	0.001	11.3
F-R	4	8.1	7.1	7.1	4	34.3	0.001	21.9	4	2.4	-	-
T-R	1	-	-	-	1	16.2	0.01	13.7	1	6.7	0.05	5.0
S-F-T	28	2.5	2.1	2.1	12	1.4	-	-	12	1.3	-	-
S-F-R	28	-	-	-	12	-	-	-	12	-	-	-
S-T-R	7	2.1	-	-	3	2.8	-	-	3	2.3	-	-
F-T-R	4	1.4	-	-	4	5.7	0.05	4.5	4	5.4	0.05	3.5
S-F-T-R	20				6				10			

*Taken from abridged table V of Statistical Tables for Biological, Agricultural and Medical Research R. A. Fisher and F. Yates: Oliver and Boyd, Industrial Experimentation, K. A. Brownlee: Chemical Publishing Co., Inc., PP 184 - 186

3) Tests 1 & 2: The first and second replications of the original experiment. These two replications comprise Set I.

4) Tests 3 & 4: The first and second replications of the experiment as amended in surface feet per minute values by the reduced diameters. These replications comprise Set II.

During the discussion of the analyses, it will be helpful for the reader to refer to the five constant feed graphs found in the appendix. Please note, these graphs are included as a visual aid, and are not to be considered as mathematically fitted curves.

Finally, the reader will note that there are three separate analyses shown in Tables 7 and 8. In the first case, all 180 readings were used to form what will be called the combined analysis. This analysis makes use of eight speeds over five feeds and two tool positions with two replications. The other two analyses are of sets I and II, and consider four speeds over five feeds and two tool positions, with two replications. The general approach of this discussion will be to investigate separately both of the set analyses, and then to compare their results with those of the combined analysis. In this manner, it will be possible to understand more fully exactly what the anslysis reveals, and exactly what happened during the course of the experiment.

In the analyses of Sets I and II, as shown in Table 8, eight of the fourteen sources of variance demonstrate significance. The minimum significance level has been set at five percent, and no investigation of significance above this level will be made. Of these eight sources, seven in each Set agree in demonstrating significance, while only two disagree. It will be best to stop at this point and investigate each individual source, commenting on its contribution to the total experiment, and determining how it influences the other sources. In order to accomplish this, the four single sources will be considered first. Since each of these four inputs shows up in the interaction terms, it is very important to become thoroughly familiar with their individual effects and the exact part each plays in the total experiment.

Table 8 shows that each of the four inputs demonstrates significance in both of the Set analyses. This situation does not, however, hold true in the combined analysis. Reference to the revised data, as shown in Table 5, and the five Constant Feed graphs found in the appendix, will aid the reader in understanding why this situation occurs. It can be seen that in Set I, Tests 1 and 2, the inverted tool consistently gives a lower value of surface finish. When examining these readings alone one immediately draws the conclusion that the use of an inverted tool in a turning operation will give a better surface finish. When the second Set is examined, however, the reverse conclusion is indicated. In Set II, the tool as used in the regular position seems to give a lower value of surface roughness. These conflicting results are further complicated by the fact that in the combined analysis, tool position shows no significance at all. The obvious cause of such results is the fact that the reversed trends cancel each other when combined in a single analysis. The important question here is not whether one tool position is better than another, but whether a difference exists between the two sets. There is no rational explanation, with regard to metal cutting theory, of these differences, nor is it possible to find any deviation from planned experimental procedure between the two sets. An obvious conclusion at this point is that in the long run, tool position, as tested in this experiment, has no marked effect on surface finish. There is, however, another possible explanation. Such an explanation would be that there is another, and as yet unmeasured, variable associated with the tool which produces these results. The fact that in both sets the analyses showed such a high degree of significance associated with the tool position variable, would seem to indicate that the above observation has much merit. In any event, the possibility of this unknown variable is worth noting, and remembering at a later time. It is still too early to reach a positive conclusion about tool position, but the available information indicates that surface finish is not affected by this variable on the average.

A second source, replication, presents much the same picture as found with tool position. Once again the variable in question proves significant in the two Set analyses, but loses this significance in the combined analysis. This action is again immediately attributable to a reversal in the magnitude of values. In Set I, Test 1 contains the higher value of the pair twenty-four times, while Test 2 has the higher value only seven times. In Set II, a similar situation is found. Test 3 yielded the higher value thirteen times, and Test 4, two times. If the only factors determining which Test would give the higher value were chance causes, it would be expected that both tests would have an equal probability of yielding the higher value. The extreme differences in high value locations experienced in this research, however, indicate that factors other than chance alone are present. For this reason it is safe to say that outside factors did have a marked influence on the individual replications, and that these factors were not held constant over the entire run of the experiment. These results indicate that there is more than a small chance that there was an unaccounted for variable influencing the results of this experiment, as first mentioned in connection with the effects of tool position. Although the reader may have already found a possible source of these variations, it will be best to delay a discussion of this subject for the time being. The reader should be aware of the fact that in the combined analysis, replication is not found to demonstrate significance. The reason for this occurrence is primarily a function of the manner in which the computer accepts and analyzes the data. If the order of tests were to be reversed for either Set in the input data, the combined analysis would show significance for the replication variable. This fact has no real significance with respect to the analysis as a whole, however. It should be noted that in the case of tool position, the cancelling effect could not be eliminated by changing the order of test.

There are two other input variables which have not been examined. These two sources, feed and speed, show results similar to each other, but somewhat different from those found for tool position and replication. In this case, both of the variables exhibit significance in all three analyses. In many respects it is to be expected that these variables would perform as they have. As was mentioned in Chapters 1 and 2, speed and feed are usually controlled to produce a prescribed surface roughness. In this experiment a wide range of speed and feed combinations was tested. The extent of this range of testing forced out the significance of these two variables. There is, however, another factor which has a direct influence on the size of the mean squares associated with the feed and speed sources. This has to do with the particular combinations of values of speeds and feeds used in the experiment. It is obvious that the highest values in Table 5 are those found for the highest feeds and lowest speeds. As was discussed earlier, these somewhat doubtful values were kept in the analysis. It is to be expected that the feed and speed variables exhibit significance. The inclusion of these data has served only to increase the value of the mean squares associated with these variables. Since the significance of the feed and speed variables was expected, no real explanation of these variables, as individuals, is required at this point. The effects of these two sources, as they act in combination with the other sources, will be discussed later.

The first part of this chapter has been devoted to a discussion of the primary analysis of this experiment. Those effects directly attributable to each of the four individual input sources have been discussed, some basic conclusions drawn, and questions for further study have been mentioned. At this point, the reader should be thoroughly familiar with the design, purpose and actual execution of the experiment, as well as how the four inputs can, and do, act independently of one another. To realize the full scope of the experiment, one must also be familiar with the manner in which the variables act jointly. It was mentioned at the beginning of this chapter that there were fourteen sources of variance, excluding the residual term, in the final analysis of the data. Of these fourteen sources, ten take the form of two or three factor interactions. The proper analysis of these terms will reveal how the variables jointly affect surface finish. The remainder of Chapter 3 will be devoted to a discussion of these interaction terms.

One further word of explanation is necessary at this point. The word "interaction" is often misused and/or misinterpreted by both analysts and readers. So that there is no question as to this writer's use of the term, "interaction" will be used in the following manner. Interaction is that effect which one input variable has upon the relation between another input variable and the observed variable. To be more specific with regard to this particular experiment, consider feed and speed as they affect surface finish. Suppose there was a formula $y = a + bx$, which described the surface finish (y), for feed (x) at a certain speed value. If by an increase or decrease in the speed value this equation became quadratic or if the slope (b) was changed, then there would be an interaction. If, however, neither of these conditions was met, there would be no interaction between the variables. In the future discussions, interaction will be defined and used as described above. This is the commonly accepted definition of interaction, and is consistent with normal usage.

Table 8 indicates that there is less agreement between the three analyses for the interaction terms than for the individual variables. A part of this is due to the peculiarities of the analysis, and the rest is due to the real results of the experiment. It was mentioned earlier that the extreme significance found for the speed and feed inputs was expected. For this reason, one might expect each term containing either of these variables to also show significance. Such a circumstance does not prove to be the case, however, as a review of Table 8 will immediately reveal. Instead, the analyses show conflicting results for these interaction terms. In Set I, none of the interactions containing the variable speed, demonstrates significance. Set II contains one speed term showing significance, while there are three in the combined analysis. Why did this happen? There are three possible answers. First, as was mentioned earlier, the degrees of freedom associated with the residual terms were altered. These alterations were not uniform over the three analyses because they were made in direct proportion to the number of readings replaced in the individual Sets. Would it make any difference if the degrees of freedom were restored to their original values? Would such a restoration change after the results of the analyses? Table 9 on the next page demonstrates the results of the analyses modified as proposed above. The comparison at the bottom of Table 9 indicates that a few changes are made in the new analysis. The revised analysis shows that four of the five terms containing the speed variable now demonstrate significance. In both Set analyses the two speed interactions show significance. What does this mean with regard to the initial analysis? At first glance, the changes mean little, since four of the five changes show significance levels of 5%, the minimum acceptable in this study. The changes do indicate clearly, however, that there is a decided difference between the two sets, since none of the changes shows complete agreement in the three analyses. This is the second of the possibilities mentioned above. Please note, this new analysis shows an interesting relationship between the variables, but cannot be used as the basis for meaningful conclusions, as no adjustment has been made for the alterations made in the original data. One may speculate as to whether or not this new analysis would agree with a similar one done on unadjusted data, but can go no further with the readings taken in this experiment.

The third of the possibilities for the lack of agreement between analyses is that in one of the Sets there is a real influence on surface finish, caused by speed in conjunction with another variable. The real answer to the question of why the interaction terms do not agree would seem to be a combination of the latter two possibilities. The investigation of the four inputs indicated that there was a decided difference between the two sets. An inspection of Table 6 reveals that there is an influence on surface finish caused by speed in combination with the other variables.

In Set I, none of the two-way speed terms shows significance. This is

TABLE NO. 9 - REVISED ANALYSIS

Source	Combined Analysis D.F.	F.	Lev.	Val.	Set I D.F.	F.	Lev.	Val.	Set II D.F.	F.	Lev.	Val.
S-F	28	2.50	0.01	2.1	12	1.65	-	-	12	6.40	0.01	4.2
S-T	7	12.66	0.001	4.7	3	3.28	-	-	3	3.90	0.05	3.5
S-R	7	5.01	0.001	4.7	3	1.02	-	-	3	3.16		-
F-T	4	1.70	-	-	4	35.52	0.001	9.60	4	24.00	0.001	9.60
F-R	4	11.38	0.001	6.3	4	68.94	0.001	9.60	4	2.86	-	-
T-R	1	-	-	-	1	32.55	0.001	18.60	1	8.04	0.05	4.8
S-F-T	28	3.64	0.001	2.7	12	2.82	0.05	2.7	12	1.57	-	-
S-F-R	28	1.27	-	-	12	1.34		-	12	1.06	-	-
S-T-R	7	2.98	0.05	2.4	3	5.70	0.05	3.5	3	2.71	-	-
F-T-R	4	1.97	-	-	4	11.51	0.001	9.6	4	6.47	0.01	5.4
S-F-T-R	28				12				12			

Comparison of Analyses

Source	Combined Analysis #1	#2	Set I #1	#2	Set II #1	#2
S-F	-	0.01	-	-	0.01	0.01
S-T	0.001	0.001	-	-	-	0.05
S-R	0.05	0.001	-	-	-	-
F-T	-	-	0.01	0.001	0.001	0.001
F-R	0.001	0.001	0.001	0.001	-	-
T-R	-	-	0.01	0.001	0.05	0.05
S-F-T	0.05	0.001	-	0.05	-	-
S-F-R	-	-	-	-	-	-
S-T-R	-	0.05	-	0.05	-	-
F-T-R	-	-	0.05	0.001	0.05	0.01
S-F-T-R	-	-				

to be expected, causes no problems, and will be left alone, lest it be disturbed. Set II does not agree with Set I with regard to the first three speed interaction terms. In the second Set, the results show that speed, when acting with feed, or vice versa, does have an additional effect on surface roughness. Note that the above relationship does not hold true in the combined analysis, an indication that only in Set II, feed and speed, in combination, affect surface finish. The lack of significance in the combined analysis also indicates that the relationship found in Set II, although substantially significant in the Set, is minor throughout the whole experiment. What causes this result for Set II? Table 6 shows that in Set I, a general relationship between feed and speed does exist. In a majority of the cases, as the speed is increased, the surface finish decreases. This relationship holds true for all of the feeds. In Set II, however, the same relationship does not hold true for the full range of feeds. In the first three feeds, the above relationship holds true. At a feed of 0.019 inches per minute, however, the relationship begins to disappear. In the final feed, 0.029 inches per revolution, the situation is completely reversed, and the values of surface roughness increase as the speed increases. This reversal of trends is the reason that the speed-feed term shows significance in Set. II. The reader will notice that this significance does not hold true in the combined analysis. The reason for this is that the overwhelming part of the entire data shows no trend for the speed-feed combination. Therefore, the small trend that was noted in part of Set II is cancelled by the rest of Set II and by all of Set I.

The remainder of the combined analysis also disagrees with the two set analyses. In this instance, speed, when acting with tool position and replication, is found to be significant. It is interesting that this relationship is found, since neither tool position nor replication was found to be individually significant. The answer to this occurrence is not too obvious, but can be drawn out of the data. In the first case, the amended analysis, Table # 9, also shows significance for this interaction in Set II. For this reason, it may be advantageous to first look at the second set. The data shows that in each case the value for the tool in the regular position at the highest speed is larger than the value at the next lower speed. This does not hold true, for the tool in the inverted position. In fact, the situation is reversed. In Set I, there is also a slight trend in the speed-tool position relationship. The reader will see that the exact reverse of what occurs in Set II, happens in Set I. Both of these trends are slight and only one even shows up in the revised analysis. Nevertheless, when the two sets are combined, the trends seem additive, and demonstrate significance at a surprisingly high level. In other words, there is an additive effect between the two sets, causing an interaction, not found to be strong in the individual analyses, to become significant in the combined study.

Finally, the speed and replication term also shows significance. Once again the individual analyses did not indicate that the combination contributed significantly to the measured values of surface finish. What is more interesting is the fact that even in the revised analyses this relationship does not show significance in either of the Sets. Obviously, there is again an additive effect present to a minor degree in each of the sets, which shows its influence only when the sets are combined. The reader should note that this interaction shows significance only at the 5%, or the minimum level studied. This means that there is a better chance for this demonstration of significance to be false than for the other sources with higher confidence levels. It does not seem, however, that this is the case in this study. The above statement may be more conjecture than fact, but no evidence is offered which indicates that the reverse is true. A complete review of the data does not seem to yield the precise nature of the implied relationship.

It should be noted, at this time, that there was a definite purpose for separating the variable "replication" from the other variables. First, there was the possibility that it could be used as the error term. In this experiment it could not, since with it set aside, the speed-feed-tool position interaction becomes the basis of comparison, and replication is significant in each Set.[3] The second reason for separating the replication term is to see what the rest of the experiment looks like with it set aside. For these reasons, no further detailed explanation of the terms involving replication will be given.

There are still three, two component interactions which have not been discussed. None of these agrees completely through the three separate analyses, but two of them do seem to demonstrate the cancellation of effects. In the first case, the feed and tool interaction, significance is shown in both set analyses, but it disappears in the combined analysis. The possibility that the significant effects are the reverse of each other is further enhanced by the fact that the identical pattern is seen in the revised analysis. The extreme value of significance found for the individual variables may have some carry-over in the interaction, but this would not conform to the definition of interaction given earlier in this

(3) For a complete analysis without replication set aside, see: Heist, H.H., Whitehouse, G.E., and Young, J. "An Investigation of the Effect of Using an Inverted Tool in Turning" on file with Prof. G. E. Kane, Lehigh University, 1961.

chapter. There should, therefore, be an easily identified relationship which causes this significance. Reference to Table #6 gives an insight into the exact nature of the demonstrated relationship. Notice that in both of the Sets, the values for the first two feeds are fairly well mixed with regard to which tool position yields the higher or lower value. As the feeds increase, however, this does not remain the case. In the two highest feeds in Set I, the inverted tool shows the lowest value each time. In Set II, the opposite is true. It would seem that this is a function of tool position and feed, and is not changed by replication.

There are four sources of variance which have not yet been discussed. These are the three-factor interaction terms, and they are very difficult to picture. In two of the terms, complete agreement is found between the three analyses. In the other two cases, there appears to be one example of additive effects, and one of cancelling effects. Because of the difficulty involved in visualizing these interactions, and since three-factor interactions are normally relegated to positions of minor importance, this writer will not discuss each term individually. Instead, it will be sufficient to comment generally on the information gained through a study of these terms.

First, two of the terms show no significance in any of the analyses. Both of these terms contain the variables speed and replication. In two factor terms, the speed-replication interaction showed significance in the combined analysis only. This level of significance was found to be the minimum considered, and no reasons for the significance were found. There is no apparent reason why either of these three-way interactions should prove to be significant, and theoretically, the term should not show a significant effect. It is interesting to note, however, one more fact concerning these two interactions. In all three analyses for the speed-feed-replication term, the mean square was less than the mean square for the residual term. This could almost be taken to mean that these three variables tend to dampen each other, when considered in combination. In second term, speed-tool position-replication, the above is not the case. The "F" ratio values observed are, however, much lower than the values found in the tables.

Secondly, the two remaining terms show exactly opposite results. In one case, the source containing speed, feed, and tool position, shows significance only in the combined analysis. Note that this was also the case in the speed and tool position interaction, but is the exact opposite of the feed-tool position interaction. Once again, there is no easily recognizable reason for this demonstration of significance. The level shown is only 5%, which was the minimum level that was considered. The reader should, however, note the fact that the demonstrated effect is cumulative over the two Sets. Such accumulation of a relationship has been found only twice before in all of the sources of variance. It is interesting to note that in both of these cases, the variable speed is present. It is very possible that the speed variable is the major contributor to the combination. It is impossible to prove whether or not the above is true, but the possibility of its truth is excellent. In the second case, there seems to be a cancellation of significant effects. This same pattern has been found in four previous cases. Note that in each of the four cases, the variables tool and/or replication are found. Also, in one of the four terms, the variable tool position is found. It is interesting to note that only these three variables, singularly or in combination, are in sources which follow the cancellation pattern. It is not possible to define exactly the causes of this pattern, but there is an excellent chance that the two variables tool-position and replication are the chief influences.

CHAPTER #4: THE RESULTS

In light of the stated purposes of this thesis, the results must be considered primarily negative in nature. This does not mean that a great deal of knowledge cannot be gained through the experiment and its analysis. What is true, however, is the fact no really positive statements can be made about the advantages or disadvantages of using an inverted tool in a turning operation. There are many factors in the experiment which lead this writer to believe that the question has not been fully answered. These factors have been mentioned in the previous chapters, and should be clear to the reader. There are, however, a few concrete results which can, and should, be extracted from the study.

First, there is a definite difference between the two Sets. This fact is substantiated by the conflicting results found in the three analyses discussed. The exact nature and/or effect of this difference has not, and cannot be accurately defined. It is obvious that in most cases, the difference was real, and had a marked effect. It is hard, however, if not impossible, to determine whether or not the removal of the Set differential would have an appreciable effect on the actual results of this experiment. The basis of this observation is the fact that there seems to be some disagreement within the Sets themselves. In any case, it is the opinion of this writer that the Set differentials were caused by either the mixing of the experimental work pieces or by the decreased diameters used in Set II. The sections used were from the same heat, and all gave the same Brinell Hardness values. There is, however, no guarantee that the micro-structure of the metal was constant throughout each piece, let alone the entire heat. It is very possible that the Set differentials are due entirely to the physical differences between the bars. There is also a second possible cause of the differences between the Sets. This is based on the consideration of the initial diameters of the bars used in each Set. There is some chance that bar diameter has a real effect on the surface finish of the piece. There does not, however, seem to be any accepted theory which would indicate that this is true when the differences are as small as found in this experiment. Either one of these reasons, or a combination of the two, should be the cause (s) of the Set differentials.

Secondly, there were the expected results concerning the variables of feed and speed. As was explained earlier, these two quantities are normally controlled to give a desired surface finish. The fact that the feed variable was so overwhelmingly significant is not surprising, but may have had some adverse effects on the experimental results. In the discussion of this variable, it was pointed out that the sum of squares around feed was exceedingly large. It is not a particularly good situation when one variable contributes a majority of the total sum of squares. There is a good chance that the magnitude of the feed variable served to dampen the effects of the other variables. This is especially true in the interaction terms. The fact that the most significant effects due to feed changes were found in the higher feeds makes the inclusion of the high feeds even more undesirable than originally expected. These readings were, however, a part of the original experimental design, and deserved to be included in the analysis of the experiment.

Thirdly, some interesting patterns were developed in the interaction terms. The additive and cancelling effects found in these terms are quite interesting, in spite of the known Set differentials. The additive effects, especially, indicate that there is a large degree of similarity between the Sets in some respects. Whether or not these effects would be found in two Sets initially considered to be alike is impossible to say at this time. It is the opinion of this writer that there would be similar, if not identical patterns found in an experiment conducted under almost any conditions. Nevertheless, the reader must be careful not to confuse effects generated by the order of the data, and those generated by the data in its entirety.

Finally, the reader should not be overly influenced by the term(s) containing the variable interaction. The precise reason for bringing out this variable was given in Chapter 3, and must be accepted at face value. It is very important that this variable be accepted as minor, and that more attention be focused on the other sources. The main effect of bringing out this variable was the further refinement of the sources containing the three major variables. In this manner, the analyst was able to see the real effects attributable to the input variables and their contributions to the total experiment.

In conclusion, the reader should be aware that this experiment has more than just passing value. There are some results which serve only to reinforce the classic theories of metal cutting. These concern the effect of speed and feed changes. Other results should bring to the reader's mind other questions which were not answered in this experiment. Finally, the reader's interest as to the precise analysis of the data should be aroused. Many assumptions, conditional manipulations, and freedoms were taken with this data. The validity of each deviation from standard procedure was taken as a matter of course by this writer. The final chapter of this thesis is devoted to suggestions for further study. These may be accepted or rejected by the reader, as he likes, but are the results of personal experience and seem sound to the writer.

CHAPTER #5: RECOMMENDATIONS FOR FURTHER STUDY

In Chapter 4, it was mentioned that this study should have brought forth many questions to the reader's mind. This is no less true for the writer than the reader. The questions in the writer's mind may be more apt to be prefixed with "What if", but the rest of the question should be similar to that of the reader. For this reason, Chapter 5 is devoted to the listing and explanation of the questions in this writer's mind. These questions will be in statement or topic form, but are nevertheless subjects in which the writer has a vital interest.

1. The experiment should be re-designed, and expanded in scope.

There were several factors, mentioned in Chapter 2, which made this experiment incomplete in its design and scope. First, it was the question of force direction which suggested that an inverted tool may yield a better surface finish. For this reason, the new experiment should include actual measurements of the forces involved. Second, human error, considered constant, undoubtedly had some effect on the experimental results. To correct this situation, a mechanical trace of the generated surfaces, combined with a graphical representation of the surface should be used to determine the real value of surface roughness. Thirdly, equal speed changes should be used. To accomplish this, a modification of the standard lathe would be required. Equal steps in speed changes would, however, be very helpful to the analyst. Fourth, the bar should be supported at both ends. Most of the readings that were discarded had to be removed because of chatter generated at the free end of the bar. The support of this free end would remove the chances of extreme chatter. Finally, the replications should be changed. No effort was made to take readings for specific combinations of feeds and speeds at different points along the bar. There may be a hidden effect within the data used in this study caused by the location, along the bar, of the individual readings. By taking readings for each combination at every tested point along the bar, this locational differential would be eliminated.

2. The data used in this study should be further modified, and re-analyzed.

In Chapter 2, it was stated that all of the feed and speed combinations used in the experiment were included in the analysis. In Chapters 3 and 4, it was mentioned that the inclusions of the questionable feeds and speeds may have adversely affected the results. For this reason it may be advantageous to divide the data into parts, and compare the results found for each part. The natural division would be to discard the two lowest speeds, and separate the three low feeds from the two high feeds. It is very possible that the variables have different effects in finishing feeds than in roughing feeds.

3. A similar experiment should be run using High Speed Steel tools.

The use of H. S. S. tools would allow the experimenter to realistically measure tool wear. Since tool wear has a real effect on surface finish, it would be worthwhile to be able to get an accurate measurement of this quantity. There is also a possibility that H. S. S. tools would show completely different results than those found for the carbide inserts. One fact should be mentioned in connection with this suggestion. The person or persons doing the research should be sure to be able to duplicate the tool geometry of the original tool. Also, the researchers should be careful to positively control tool over-hang.

4. An experiment should be designed utilizing the reversal of the direction of rotation.

In the experiment discussed in this paper, the inversion of the tool was accomplished by using the rear tool position on the lathe. The direction of rotation remained constant throughout this experiment. Since the direction of feed was also the same for both tool positions, two right-handed tool holders were used. If the direction of rotation were changed for each position, and inversion were accomplished by using only the front (or rear) tool post, one right-hand and one left-hand tool holder would be required. The use of the front tool post only, is more realistic for shop use, with regard to normal lathe usage.

5. This same data should be re-analyzed by a different method.

It was mentioned earlier that one particularly useful form of analysis may have been advanced curve fitting. There may also be other types of analysis which would bring out the information found in this report in a different manner.

6. An experiment should be designed to particularly single out the causes of the Set differentials.

In Chapter 4, it was mentioned that one possible cause of the Set differential was the differences in the initial diameters of the bars. The testing of this theory should be an interesting and valuable experiment. By designing an experiment, using one or both of the tool positions, which uses different R.P.M. and bar diameters to produce the same speed values, one should be able to fully answer this question.

- APPENDIX -

ILLUSTRATION NO. 1: SAMPLE CALCULATIONS

I S of Ind. Squares $= 1,236,314 + x^2 + y^2$

II S Row Totals (Sq.) $= 1/5\ (3,604,248 + 1920x + 1832y + x^2 + y^2)$

III S Col. Totals (Sq.) $= 1/4\ (5,055,666 + 592x + 480y + x^2 + y^2)$

IV S Obs. Squared $= 1/20(x^2 + y^2 + 2xy + 7592x + 7592y)$

Error $= (I + IV) - (II + III)$
$= 12x^2 + 12y^2 + 2xy - 3048x - 2136y$

$$20\,\frac{dE}{ax} = 24x + 2y - 3048 = 0 \qquad 12x + y = 1524$$

$$20\,\frac{dE}{ax} = 24y + 2x - 2136 = 0 \qquad 12y + x = 1068$$

$$144y + 12x = (12)(1068)$$

$$143y = (12)(1068) - 1524$$

$$y = \frac{11292}{143} = 78$$

$$x = 121$$

Values Used:

$y - 70$

$x - 150$

$$\text{I} \quad S \quad \text{Ind. Sqs.} = (2{,}464{,}535 + x^2 + y^2)$$

$$\text{II} \quad S \quad \text{Row Totals (Sqd)} = 1/10(x^2 + y^2 + 3400x + 3500y)$$

$$\text{III} \quad S \quad \text{Col. Totals (Sqd)} = 1/8\ (x^2 + y^2 + 2xy + 740x + 700y)$$

$$\text{IV} \quad S \quad \text{Obs. (Sqd)} = 1/40(x^2 + y^2 + 2xy + 14970x + 14970y)$$

$$\text{Error} = E = (\text{I} + \text{IV}) - (\text{II} + \text{III})$$
$$= 32x^2 + 32y^2 - 8xy - 2330x - 2730y$$

$$40\frac{dE}{dx} = 64x - 8y - 2330 = 0$$

$$40\frac{dE}{dy} = 64y - 8x - 2730 = 0$$

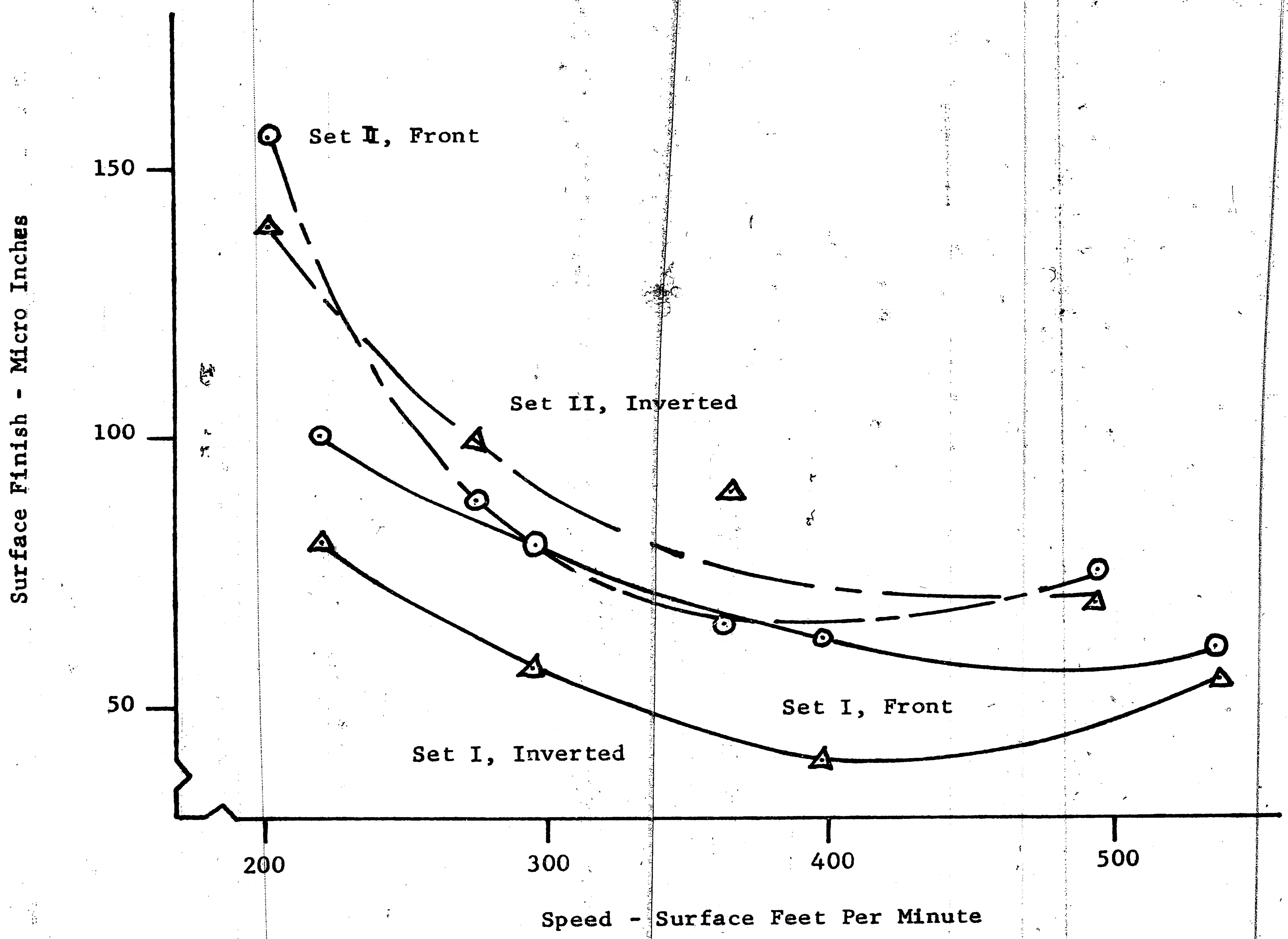
$$448x = 20470 \qquad X = 45.7$$

$$64y = 3095 \qquad y = 48.3$$

Values Used:

Y - 40

X - 55



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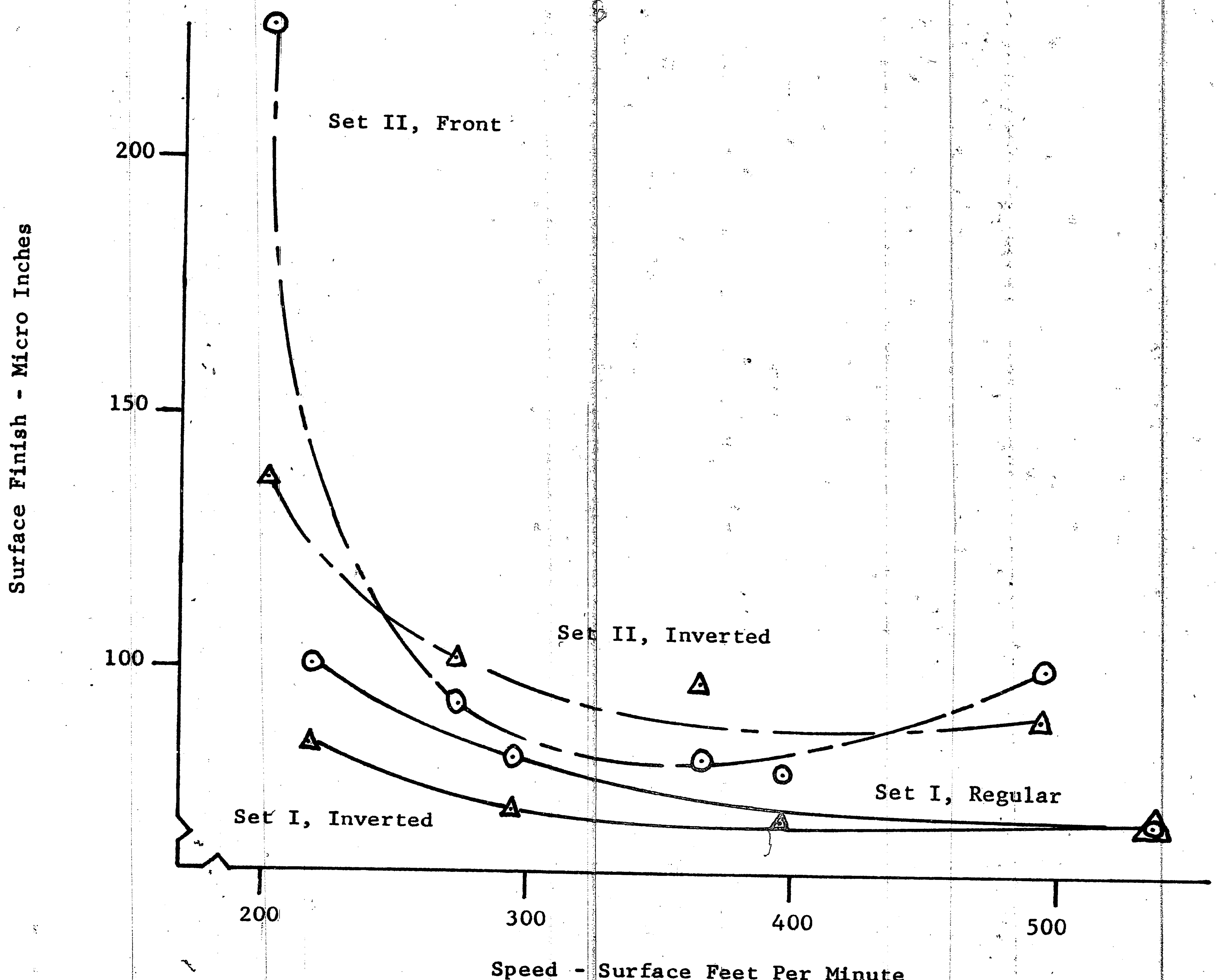

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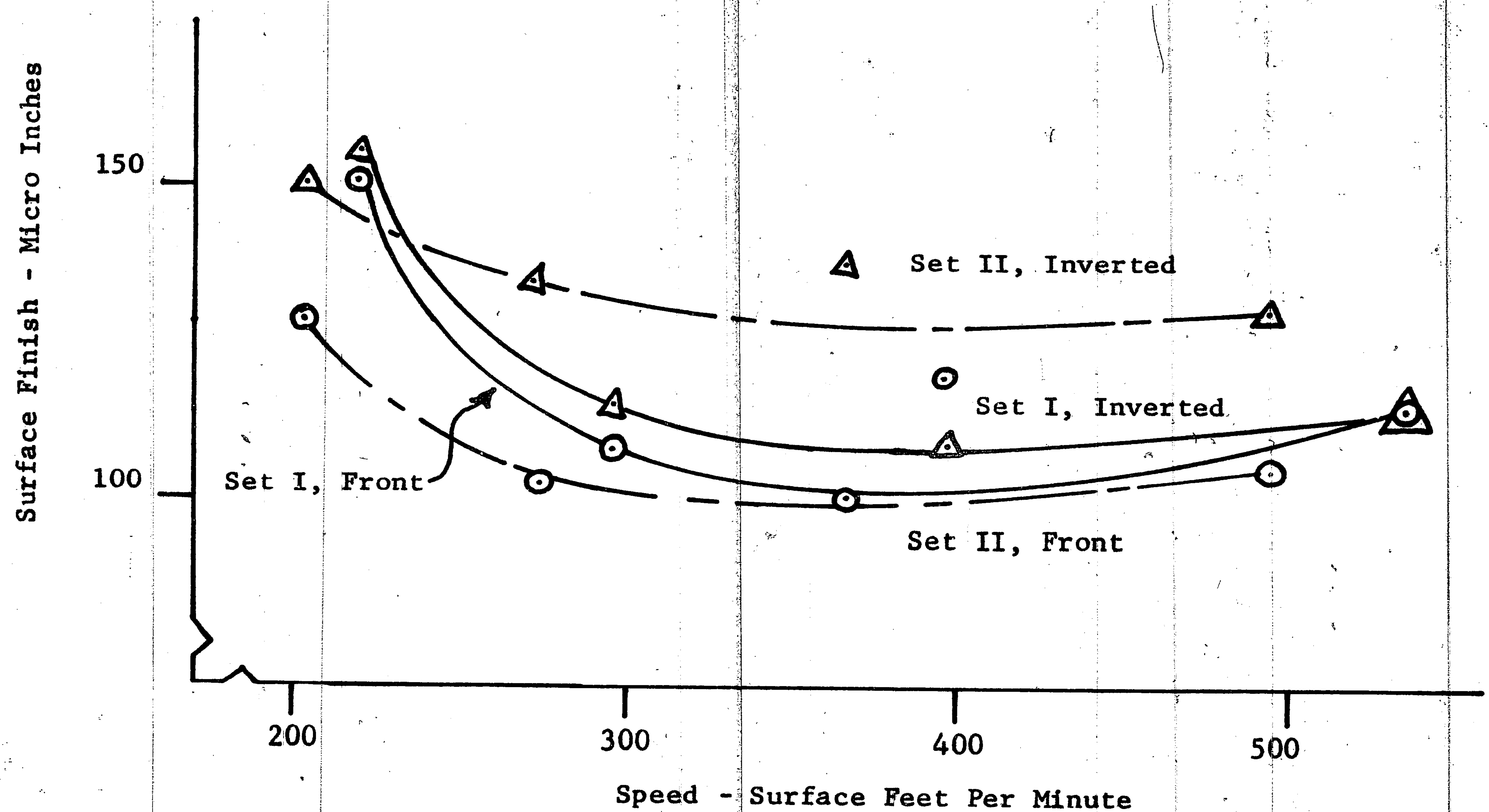

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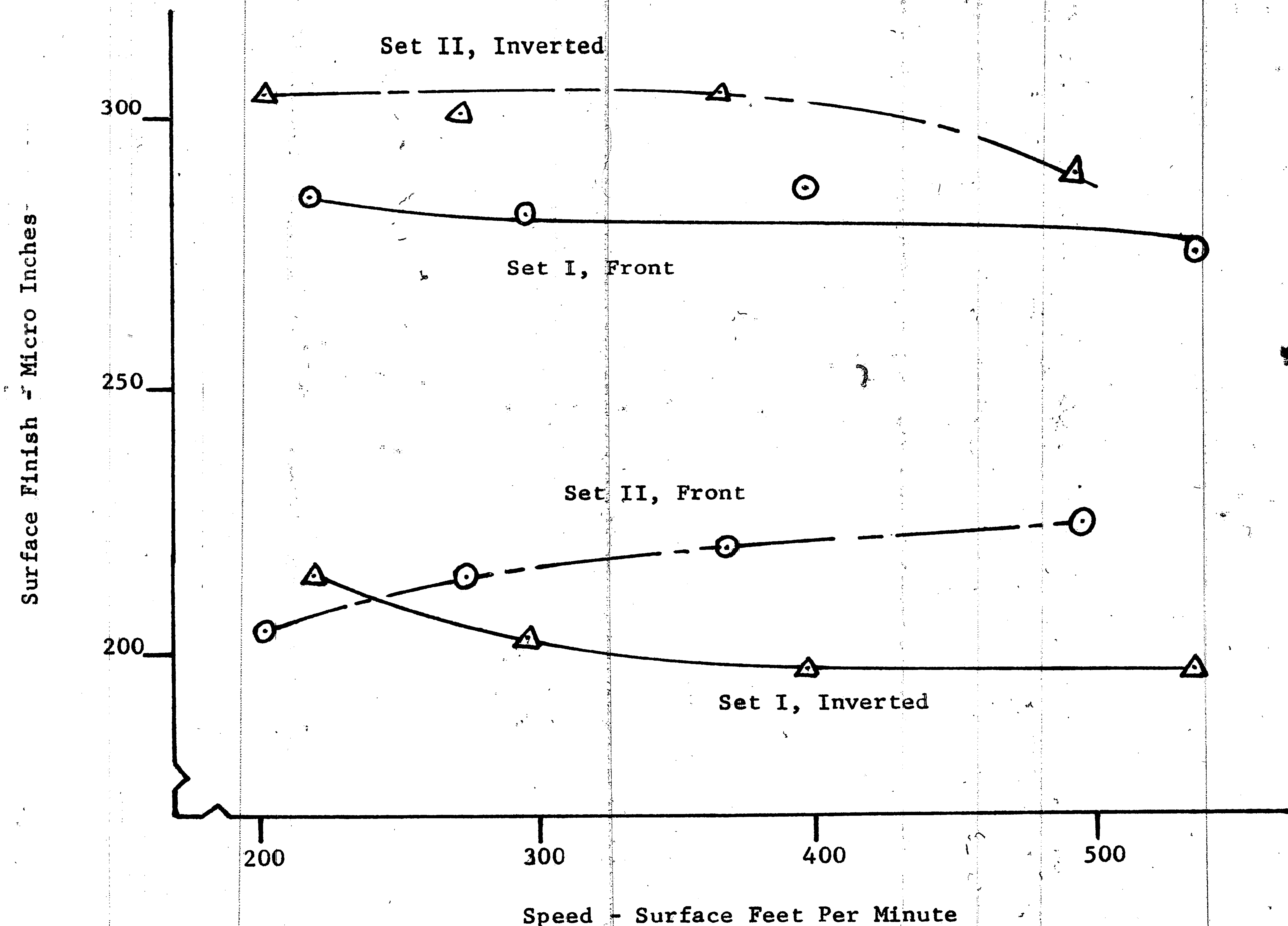

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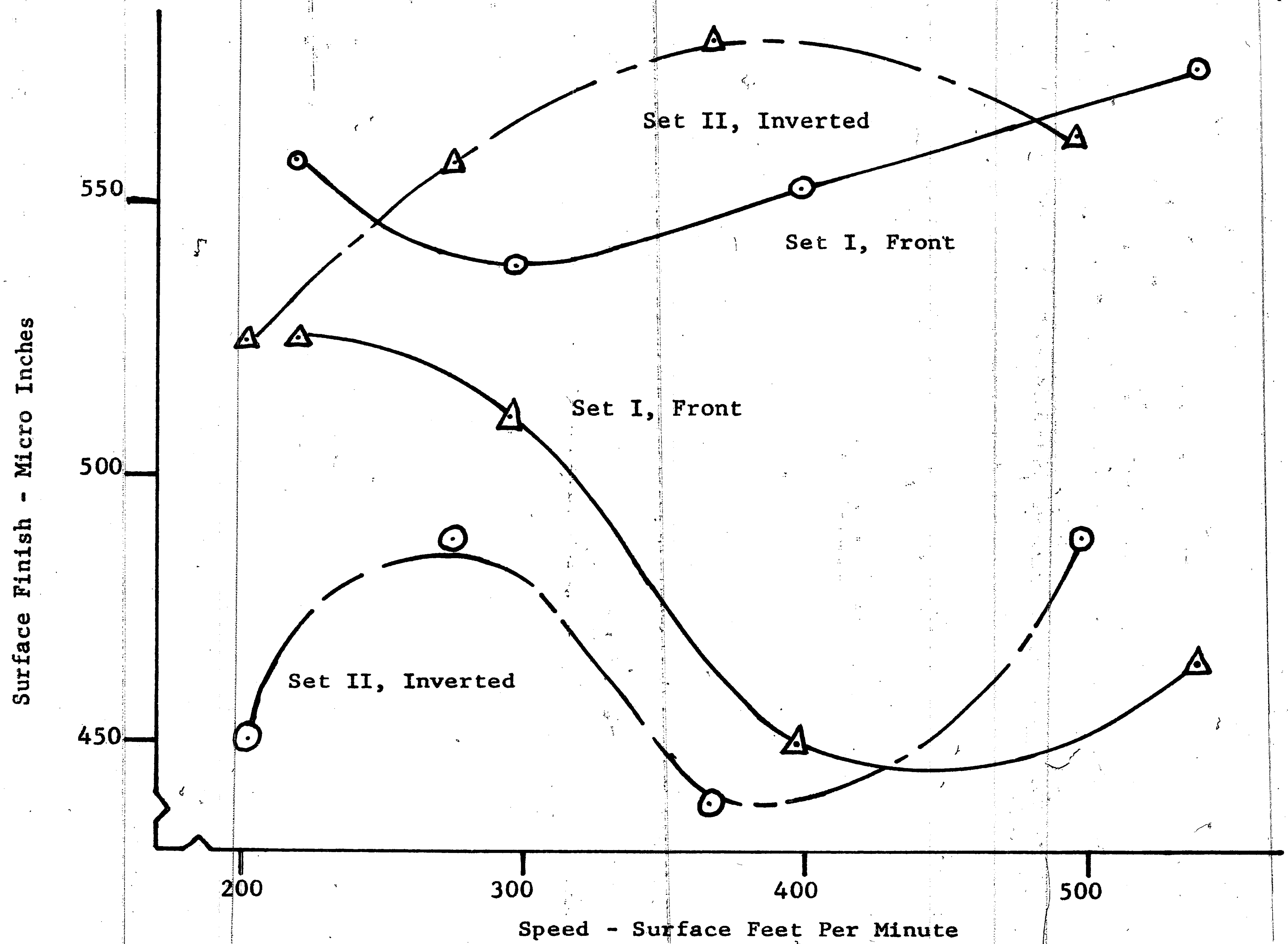

Illustration No. 5 F = 0.029"/Rev.

ILLUSTRATION NO. 7 - COMPUTER OUTPUT

Source	DF	SS	MS
a	00000007.	00029890.	00004270.
b	00000004.	04219612.	01054903.
c	00000001.	00000082.	00000082.
d	00000001.	00003543.	00003543.
ab	00000028.	00045935.	00001640.
ac	00000007.	00058238.	00008319.
ad	00000007.	00023036.	00003290.
bc	00000004.	00004478.	00001119.
bd	00000004.	00029910.	00007477.
cd	00000001.	00000096.	00000096.
abc	00000028.	00066960.	00002391.
abd	00000028.	00023338.	00000833.
acd	00000007.	00013725.	00001960
bcd	00000004.	00005170.	00001292.
abcd	00000028.	00018405	00000657.
abcde	00000000.	00000000.	00000000.
Total Sx	00000159.	04542418.	
S	00034235.		

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